

# NONLOCAL EFFECTS ON THE POLARIZATION STATE OF A PHOTON, INDUCED BY DISTANT ABSORBERS

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## Abstract

A variant of a Franson's two-photon correlation experiment is discussed, in which the linear polarization state of one of the photons depends on the path followed in the interferometer. It is shown that although the path difference is greater than the coherence length, the photon can be found in a polarization state represented by the superposition of the polarization states associated to the paths when there is coincident detection. Since the photons, produced via parametric down-conversion, are fairly well localized in space and time, the situation in which one of the photons is detected before the other can reach the interferometer raises an intriguing point: it seems that in some cases the second photon would have to be described by two wave packets simultaneously. Unlike previous experiments, in which nonlocal effects were induced by means of polarizers or phase shifters, in the proposed experiment nonlocal effects can be induced by means of variable absorbers.

Ever since Bell's theorem [1] and the important paper by Clauser, Horne, Shimony, and Holt [2], different experiments have been performed related to quantum mechanical nonlocality. In these experiments the photons of a correlated pair either are made to impinge on polarizers [3] or are made to pass through phase shifters [4,5]. Here I would like to discuss an experiment (represented in Fig. 1) in which nonlocal effects can be induced by means of variable absorbers (or variable beam-splitters). It is a modified Franson's experiment [5], in which a half-wave plate ( $\lambda/2$ ), a two-channel polarizer, and two variable absorbers ( $A_S$  and  $A_L$ ) have been included. Photons  $\gamma_1$  and  $\gamma_2$ , produced via parametric down-conversion, are in the same polarization state [6], which I will assume as being parallel to  $x$ . The orientation of the half-wave plate is chosen so that after passing it  $\gamma_2$  is in a different polarization state, perpendicular to the state it was in. As has been shown [7], when there is coincident detection, the packets following the long ( $L_2$ ) and the short ( $S_2$ ) paths interfere. In the present proposal the relative amplitude of these packets is varied at a distance by means of  $A_S$  and  $A_L$ . For our purposes, we only need to consider a field with one polarization component. When the beam-splitters  $H_1, H_2, H'_1$  and  $H'_2$ ; the absorber  $A_S$ ; and the half-wave plate are removed,  $\gamma_1$  and  $\gamma_2$  can only follow the short paths, and the coincidence rate between the detectors at sites 1 and 2 is given by [8]

$$R_0 = k \langle t | \hat{E}_{2S}^{(-)}(t) \hat{E}_{1S}^{(-)}(t) \hat{E}_{1S}^{(+)}(t) \hat{E}_{2S}^{(+)}(t) | t \rangle, \quad (1)$$

where  $|t\rangle$  is the state of the field at time  $t$ ;  $\hat{E}_{2S}^{(+)}(t)$  is the annihilation part of the electric field operator at the detector at site 2; and so on, and  $k$  is a proportionality constant. If, instead

of removing the beam-splitters, they are replaced by mirrors and  $A_L$  is removed,  $\gamma_1$  and  $\gamma_2$  can only follow the long paths, and the coincidence rate between the detectors at sites 1 and 2 is given by

$$R_0 = k \langle t | \hat{E}_{2L}^{(-)}(t) \hat{E}_{1L}^{(-)}(t) \hat{E}_{1L}^{(+)}(t) \hat{E}_{2L}^{(+)}(t) | t \rangle . \quad (2)$$

$\hat{E}_L^{(+)}(t)$  and  $\hat{E}_S^{(+)}(t)$  are related by the expression

$$\hat{E}_{jL}^{(+)}(t) = e^{i\phi_j} \hat{E}_{jS}^{(+)}(t - \Delta T) , \quad j = 1, 2, \quad (3)$$

where  $\Delta T = (L - S)/c$ , with  $L = L_2 = L_1$  ( $S = S_2 = S_1$ ) representing the length of the long (short) path, and  $\phi_j$  is a phase shift. Since  $L - S$  is much greater than the coherence lengths of the wave packets associated with  $\gamma_1$  and  $\gamma_2$ ,

$$\hat{E}_{1L}^{(+)}(t) \hat{E}_{2S}^{(+)}(t) | t \rangle = 0 \quad (4)$$

and

$$\hat{E}_{1S}^{(+)}(t) \hat{E}_{2L}^{(+)}(t) | t \rangle = 0 . \quad (5)$$

Since  $\Delta\omega\Delta T \ll 1$ , where  $\Delta\omega$  is the uncertainty in the sum of the frequencies of  $\gamma_1$  and  $\gamma_2$ , it can be shown that [5]

$$\hat{E}_{1S}^{(+)}(t - \Delta T) \hat{E}_{2S}^{(+)}(t - \Delta T) = e^{i(\omega_{10} + \omega_{20})\Delta T} \hat{E}_{1S}^{(+)} \hat{E}_{2S}^{(+)}(t) , \quad (6)$$

where  $\omega_1 + \omega_2 = \omega_{10} + \omega_{20} \pm \Delta\omega$ , and  $\omega_{10}(\omega_{20})$  is the central frequency of  $\gamma_1(\gamma_2)$ .

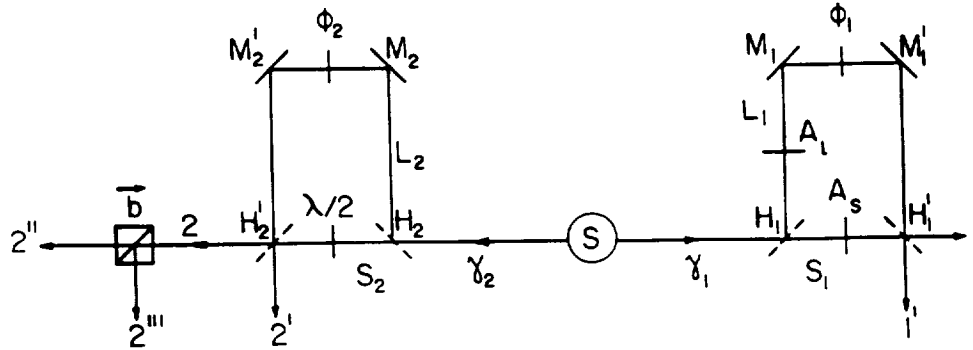


FIG. 1. Franson's experiment in which a half-wave plate, a polarizer, and two absorbers have been included.

To represent the action of the absorbers, I will introduce a parameter  $\theta$ , such that:

$$\hat{E}_{1S}^{(+)}(t) \xrightarrow{A_S} \sin \theta \hat{E}_{1S}^{(+)}(t) \quad (7)$$

and

$$\hat{E}_{1L}^{(+)}(t) \xrightarrow{A_L} \cos \theta \hat{E}_{1L}^{(+)}(t) . \quad (8)$$

Therefore, the transmissivities of the absorbers are varied in a correlated way. The field operator at site 1 in the experiment represented in Fig. 1. will then be given by

$$\hat{E}_1^{(+)}(t) = \frac{1}{2} \left[ \sin \theta \hat{E}_{1S}^{(+)}(t) + \cos \theta \hat{E}_{1L}^{(+)}(t) \right] . \quad (9)$$

If  $\mathbf{b}$  is the orientation of the polarizer and  $\angle(\mathbf{b}, \mathbf{x}) = \varphi$ , then when the half-wave plate is in place, the field operators at sites  $2''$  and  $2'''$  are given by

$$\hat{E}_{2''}^{(+)}(t) = \frac{\alpha}{2} [\sin \varphi \hat{E}_{2S}^{(+)}(t) + \cos \varphi \hat{E}_{2L}^{(+)}(t)] \quad (10)$$

and

$$\hat{E}_{2'''}^{(+)}(t) = \frac{\beta}{2} [\cos \varphi \hat{E}_{2S}^{(+)}(t) + \sin \varphi \hat{E}_{2L}^{(+)}(t)] , \quad (11)$$

where  $\alpha$  and  $\beta$  are phase factors.

It is then easy to show, using (1), (3), (4), (5), (6), (9), and (10) and choosing  $\phi_1 + \phi_2 = -(\omega_{10} + \omega_{20}) \Delta T + 2n\pi$  ( $n$  is an integer), that the coincidence rate between the detectors at sites 1 and  $2''$  is given by

$$R_{2''1}^c = k \langle t | \hat{E}_{2''}^{(-)}(t) \hat{E}_1^{(-)}(t) \hat{E}_1^{(+)}(t) \hat{E}_{2''}^{(+)}(t) | t \rangle = \frac{R_0}{16} \cos^2(\theta - \varphi) . \quad (12)$$

Similarly,

$$R_{2'''1}^c = k \langle t | \hat{E}_{2'''}^{(-)}(t) \hat{E}_1^{(-)}(t) \hat{E}_1^{(+)}(t) \hat{E}_{2'''}^{(+)}(t) | t \rangle = \frac{R_0}{16} \sin^2(\theta - \varphi) . \quad (13)$$

We see from (12) and (13) that, for coincident detection, whenever we have detection at site 1, if  $\gamma_2$  follows the direction to 2, it impinges on the polarizer in a polarization state parallel to  $\mathbf{c}$ , such that  $\angle(\mathbf{c}, \mathbf{x}) = \theta$ . (12) and (13) then follow from Malus' law. We can also easily verify that whenever we have detection at site  $1'$ , if  $\gamma_2$  follows the direction to  $2'$ , it also impinges on the detector in a state parallel to  $\mathbf{c}$ . By a similar procedure we also easily verify that whenever we have detection at site  $1(1')$ , if  $\gamma_2$  follows the direction to  $2'(2)$ , it impinges on the detector (polarizer) in a polarization state parallel to  $\mathbf{d}$ , such that  $\angle(\mathbf{d}, \mathbf{x}) = -\theta$ . Since  $\gamma_1$  and  $\gamma_2$  are fairly well localized in space and time [9], these results are totally counterintuitive.

The nonlocal aspects of the experiment I am discussing can be made more evident by comparing the following two situations. In the first, the beam-splitter  $H'_1$  is removed. To simplify the argument, we can consider the ideal situation in which all photons are detected. We then easily see that

$$R_{2''1}^c = \frac{1}{8} \sin^2 \theta \sin^2 \varphi \quad (14)$$

and

$$R_{2'''1'}^c = \frac{1}{8} \cos^2 \theta \cos^2 \varphi , \quad (15)$$

which correspond, respectively, to the possibilities " $\gamma_1$  and  $\gamma_2$  following the short paths" and " $\gamma_1$  and  $\gamma_2$  following the long paths". In the second situation  $H'_1$  is in place. Then, whenever  $\gamma_1$  is detected, we know that, if  $H'_1$  were not in place,  $\gamma_1$  would have been detected either at site 1 or at site  $1'$ . Thus,  $\gamma_2$  must either follow the long or the short path, as when  $H'_1$  is not in place, according to the locality assumption, since, it is irrelevant whether  $H'_1$  is in place or not. As a consequence, one must have

$$R_{2''1}^c = \frac{1}{16} (\sin^2 \theta \sin^2 \varphi + \cos^2 \theta \cos^2 \varphi) , \quad (16)$$

in strong disagreement with (12). In particular, when  $\varphi = \pi/4$ , (16) leads to  $R_{2''1}^c = 1/32$ , whilst (12) leads to  $R_{2''1}^c = (1/16) \cos^2(\theta - \pi/4)$ , where  $0 \leq \theta \leq \pi/2$ .

As I have emphasized elsewhere [7], the situation in which  $\gamma_1$  is detected before  $\gamma_2$  can reach the interferometer raises an intriguing point: it seems that  $\gamma_2$  would have to be described by two wave packets simultaneously. When  $\gamma_1$  is detected before  $\gamma_2$  can reach the interferometer, the possibilities corresponding to “both photons following the long paths” and to “both photons following the short paths” remain indistinguishable, and results (12) and (13) are still obtained. (If this were not so, special relativity might be in trouble, since the detections of  $\gamma_1$  and  $\gamma_2$  are events separated by a space-like interval. Therefore, the order in which they occur depends on the Lorentzian frame in which the experiment is being described. On the other hand, the detection rates must be Lorentz invariant quantities). The packets associated with  $\gamma_2$  correspond to the following two possibilities:  $(L_1)\gamma_1$  follows path  $L_1$ ; and  $(S_1)\gamma_1$  follows path  $S_1$ . These packets are split at  $H_2$ , producing four packets. The packet following  $L_2$  in possibility  $(L_1)$  — packet  $(L_2, L_1)$  — interferes with the packet following path  $S_2$  in possibility  $(S_1)$  — packet  $(S_2, S_1)$  — producing a packet (I) in a polarization state different from those that would have occurred, had  $\gamma_2$  followed either path  $L_2$  or path  $S_2$ . It is in this packet (I) that  $\gamma_2$  is to be found when there is coincident detection. In the experiment that I am discussing, the amplitudes of the packets  $(L_2, L_1)$  and  $(S_2, S_1)$  depend on the parameter  $\theta$ . In the previous experiments, one acted either on the polarization [3] or on the phase [4,5] of the correlated photons to induce nonlocal effects. In the present proposal, the action is on the amplitudes. If we were to act also on the phases, polarization states different from those discussed here could be produced.

This experiment could be performed using the recently improved time resolution techniques [10].

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